SUPER-RESOLUTION SPECTRAL ANALYSIS FOR ULTRASOUND SCATTER CHARACTERIZATION

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Introduction

Motivation

- Parametric Bayesian spectral estimation outperforms the conventional Fourier Transform (FT) based methods at the expense of computational time.
- Increased frequency resolution in ultrasound signal analysis may reveal new diagnostic information.

Research Question

- Can ultrasound signals be fully characterized (frequency, amplitude, phase, noise) based on Bayesian spectral estimation?

Summary

Background

- In ultrasound, the reflected echoes from point scatterers, are short sinusoidal signals with many closely spaced frequency components.
- The frequency resolution attained by the FT is limited by the small number of signal samples.
- Prior knowledge and parametric spectral estimation can be used to extract previously hidden signal characteristics.

Objective

- Reconstruct real ultrasound signals based on an already existing rjMCMC algorithm.
- Reduce the calculation load the method introduces.
- Compare the initial and reconstructed signal and identify the benefits of the parametric estimation.

Approach

- Apply a modified rjMCMC algorithm to the acquired ultrasound point scatter data.
- Extract a reasonable summary of the algorithm's output through clustering, outlier rejection and signal comparison.

Results

- The correlation coefficient between the original and the (noise-free) reconstructed signal is measured to 0.987.
- The minimum difference between neighboring frequencies that are both identified by the parametric approach is 110 kHz, whereas the FT theoretical limit is 220 kHz.
- The burn-in period of a single algorithm realization is reduced by 20%

Bayesian Inference

- Parametric estimation assumes a signal model and the received echoes are represented as a sum of sines and cosines in white Gaussian noise.
- A prior distribution is selected for each of the unknown model parameters:

Parameter	Prior distribution
Model order (k)	Truncated Poisson Distribution
Frequencies (ω_k)	Uniform Distribution
Amplitudes (a_k)	Multivariate Normal Distribution
Noise variance (σ_k^2)	Jeffrey's uninformative prior
Hyperparameter of k (Λ)	Gamma Distribution
Hyperparameter of a_k (δ^2)	Inverse Gamma Distribution

- The joint prior distribution is given by the product of all individual priors and the joint posterior distribution can be calculated as:

$$p(\Psi \mid y) = \frac{p(\Psi)p(y \mid \Psi)}{p(y)} \propto p(\Psi)p(y \mid \Psi) , \quad (1)$$

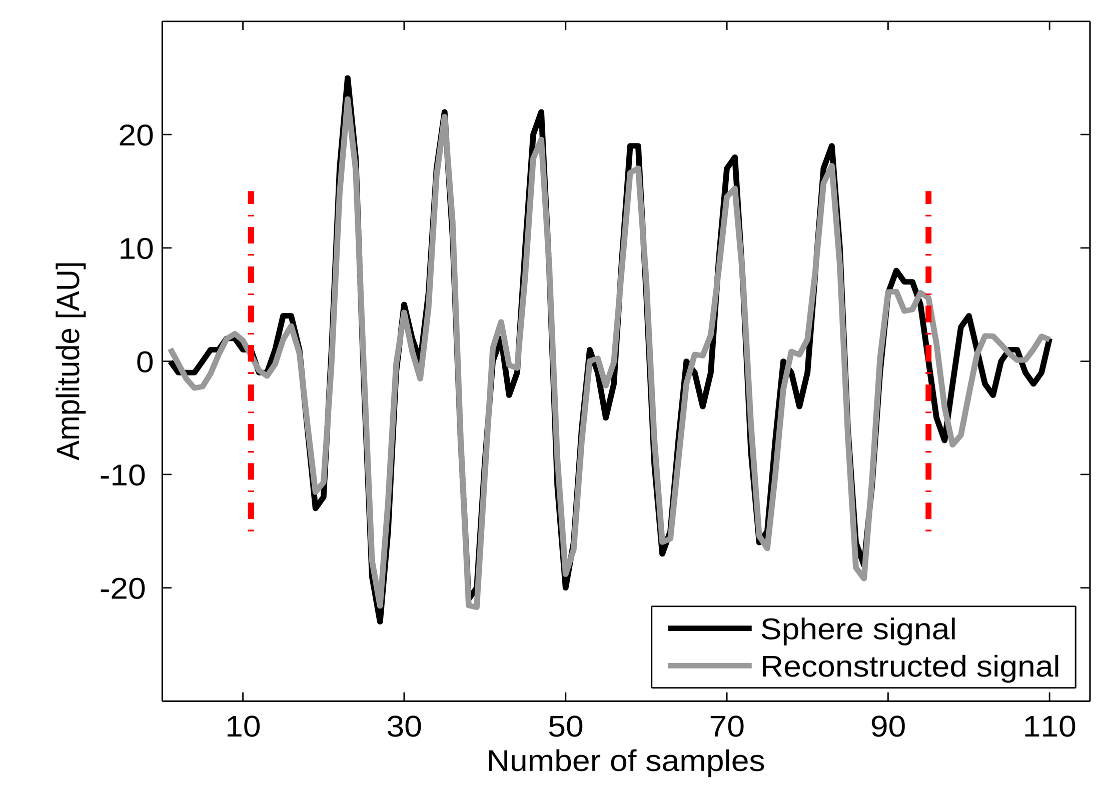
where $\Psi = (k, \{\omega_k, a_k, \sigma_k^2\})$, $p(\Psi)$ denotes the joint prior distribution and $p(y \mid \Psi)$ the likelihood function.

rjMCMC Algorithm

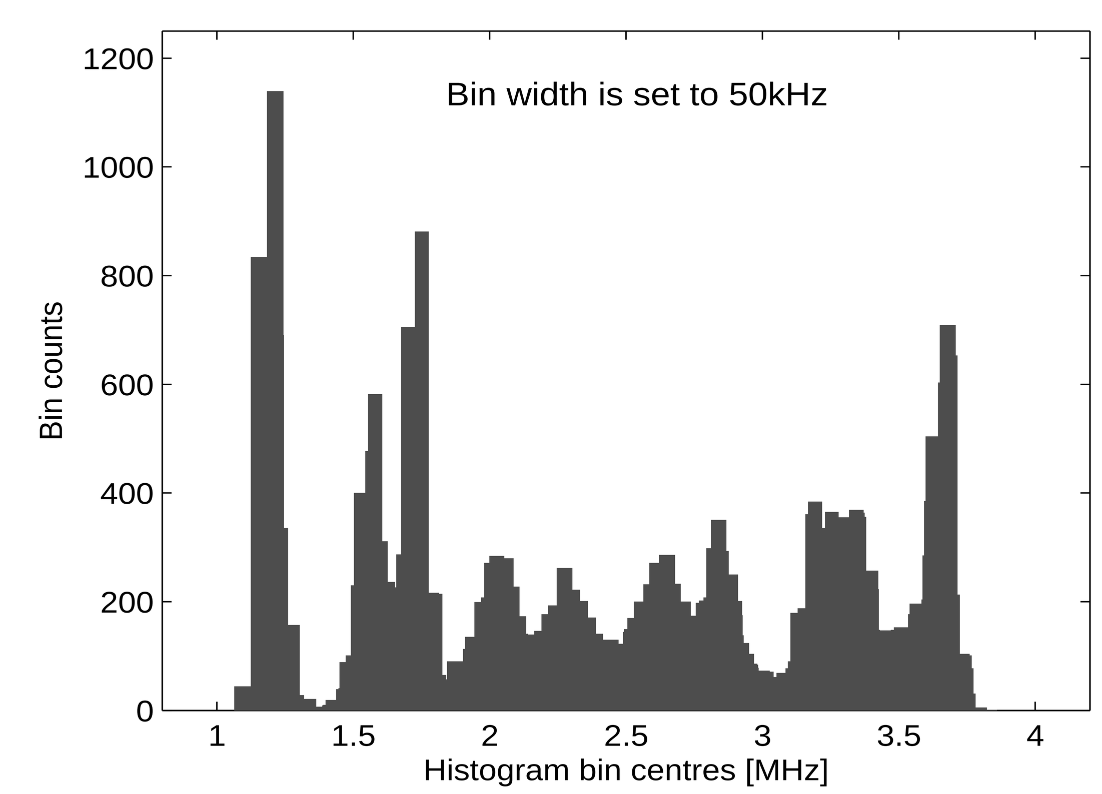
Insert the input signal to the algorithm
Employ the MUSIC method to provide an initial spectrum estimate: $(k^{(0)}, \{\omega_k, a_k, \sigma_k^2\}^{(0)})$
for $i = 1$ to numIteration **do**
  Sample Λ, δ^2
  Sample u from $U_{(0,1)}$ (uniform distribution)
  Calculate the probabilities b_k and d_k based on $\frac{p(k+1)}{p(k)}$ and $\frac{p(k-1)}{p(k)}$ respectively
  if $u \leq b_{k(i)}$ **then**
    Propose a new frequency randomly on $[0, \pi)$ and accept it with a probability of α_B (*birth move*)
  else if $u \leq b_{k(i)} + d_{k(i)}$ **then**
    Remove an existing frequency randomly from ω_k and accept it with a probability of α_D (*death move*)
  else
    Update for all k frequencies according to a proposal distribution and accept it with a probability α_U (*update move*)
  end if
  Sample nuisance parameters a_k and σ_k^2
end for
Separate estimates based on k
Remove outliers from a_k
Extract mean for ω_k, a_k *and* σ_k^2
Reconstruct signal

Measurement Setup

- A modified ultrasound transducer (Sonos5500 Philips Medical Systems) is used to acquire echo signals from solid copper spheres (SCSs).
- The experimental setup consists of a water tank and tubing that allows the drop of SCSs by gravity.
- The received response of a 6-cycle SCS signal, where the transmit frequency is 1.62 MHz and the sampling frequency is 20 MHz is shown below:

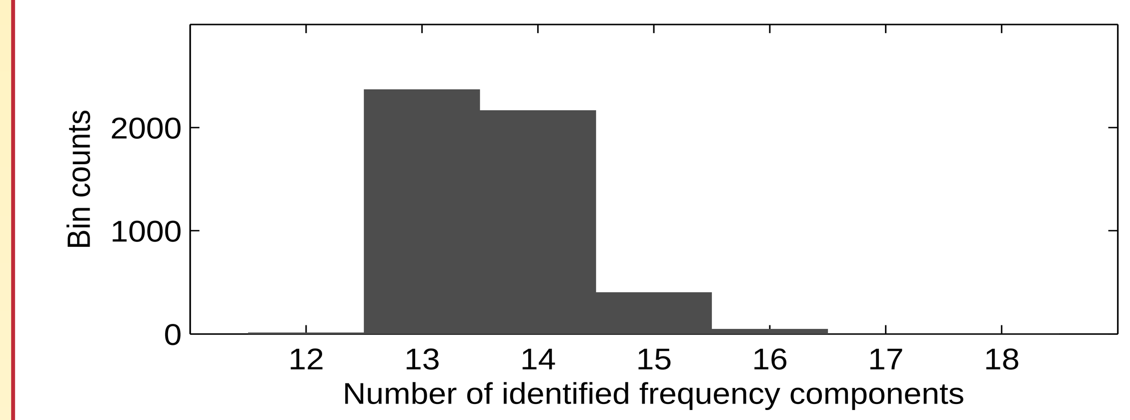


Frequency Analysis

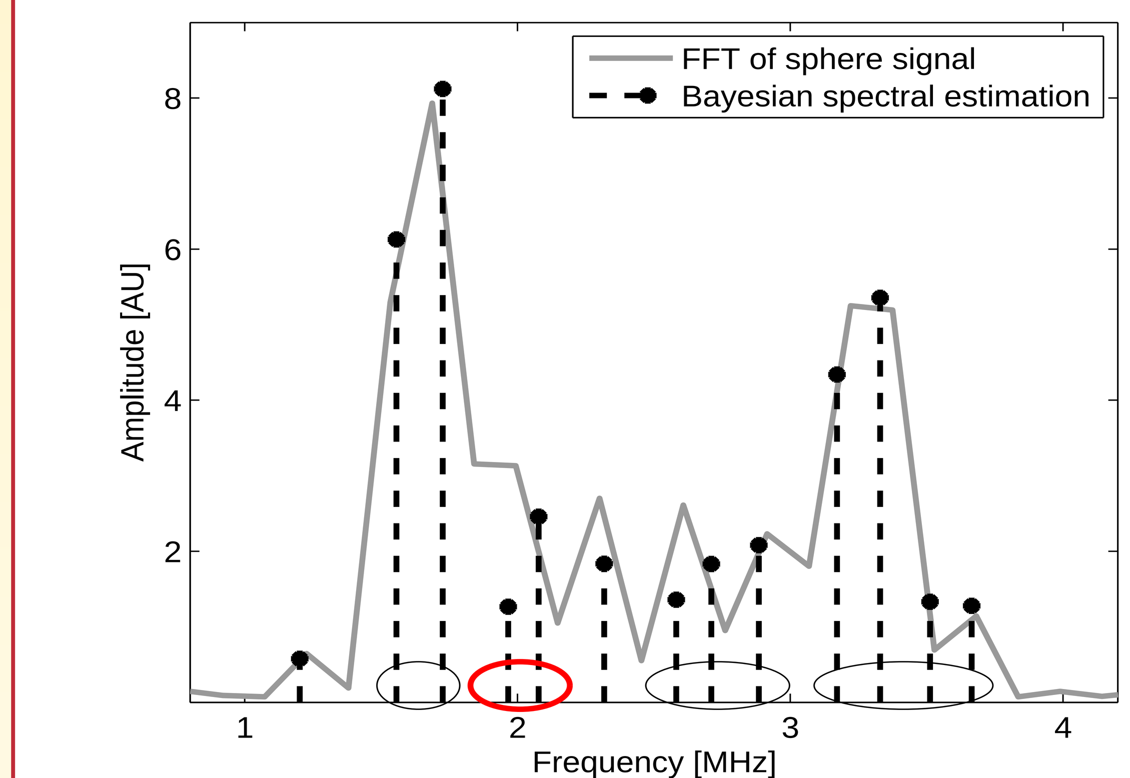


- Histogram displaying the cumulative distribution of the estimated frequency components from 5000 realizations.
- A 50 kHz bin width was used. Nine peaks can be clearly distinguished while four of them may correspond to two peaks merged to one.

Comparison with the FFT



- Histogram showing number of identified frequency components for the 5000 realizations of the rjMCMC method.



- Comparison of the FFT of the initial sphere signal with the output of the parametric spectral estimation.
- The Bayesian method results in individual amplitude and frequency values instead of a spectrum.

Conclusion

- The parametric spectral estimation provides a reconstructed signal with close resemblance to the echo signal.
- Minimum frequency separation is improved by a factor of two compared to FFT.
- The method may significantly improve the sensitivity and the specificity of existing diagnostic examinations.